2.3 GPS Device List

The list of 29 GPS devices tested is provided below.

General location and navigation (NMEA)
Garmin GPSMAP 76 CSx (Tested in 2011)
Garmin Montana 650t
Garmin eTrex H (Tested in 2011)
Garmin GPSMAP 78 SC
Motorola MW810
Trimble TM3000
Furuno GP32
General location and navigation (Non NMEA)
Motorola APX 7000
Garmin Nuvi 2495LMT
Wabtec Navigation Sensor Module
Garmin Nuvi 55LM
Garmin Nuvi 2597LMT
High precision (Live Sky)
NovAtel Smart6 or Smart6-L
NAVCOM SF-3050
Trimble Net R9
Trimble R8s Rover
Deere Starfire 3000
High precision (Open Sky)
Trimble AgGPS 542
Trimble SPS855 GNSS Receiver
Topcon SGR-1
Topcon System 310
Trimble Geo 7x
Trimble SPS985
Topcon HiPer V
Aviation (non-certified)
Garmin GPSMAP 696
Cellular (3GPP A-GPS)
Samsung Galaxy S5
Samsung Galaxy S6
iPad (w/ cellular data)
Cellular (Open Sky)
Samsung Galaxy Tab 4G LTE

2.4 Antennas

Listed below are some antennas that are resilient to adjacent channel signals.

Vendor	Class	Model
PCTel	Mobile	3915D-HR
PCTel	Mobile	8171D-HR
JAVAD gr-Ant-G3t (LSQ Provided)	High Precision	N/A

2.5 Radiated Measurements

Radiated tests are performed since they closely model real world conditions and allow the antenna to be included in the paths of both the GPS and LTE signals. Conducted tests are not feasible for devices with internal antennas. Compared to a conducted test, the LTE signal levels have to be amplified significantly to compensate for the propagation losses in an RF anechoic chamber. The GPS and WAAS signals also have to be produced at levels high enough to compensate for the chamber losses. Simulated WAAS signals are added to the applied signals when the GPS receiver is capable of receiving and processing them.

Several different radiated GPS signal conditions are used: 1) Static GPS device with simulated Open Sky GPS received signal conditions; 2) Simulated GPS device motion with simulated Open Sky GPS received signal conditions, 3) Simulated GPS device motion with simulated impairment (identically reduced power on all satellites) to GPS received signal conditions and 4) Live Sky GPS signals collected with a static roof top antenna, amplified, and radiated inside the anechoic chamber. The different radiated methods are documented in Section 2.6.3. LTE signals were presented according to the power levels described below.

The diagram in Figure 4 below shows the basic schematic of the radiated tests. A computer shown on the left, or a test engineer, controls the signal frequencies and levels while the computer on the right records the desired KPI information.

Not shown in Figure 4 is the means for ensuring the correct LTE signal level at the GPS receiver, which is based on measuring the received LTE power with a calibrated antenna of known gain placed in the position of the Device under test and oriented toward the LTE emitter. The LTE signals need to be amplified significantly to be able to apply up to -10 dBm LTE power at the GPS device under test. Both the free space path loss in the chamber and the high peak to average ratio of the LTE waveform need to be considered in the choice of amplifier.

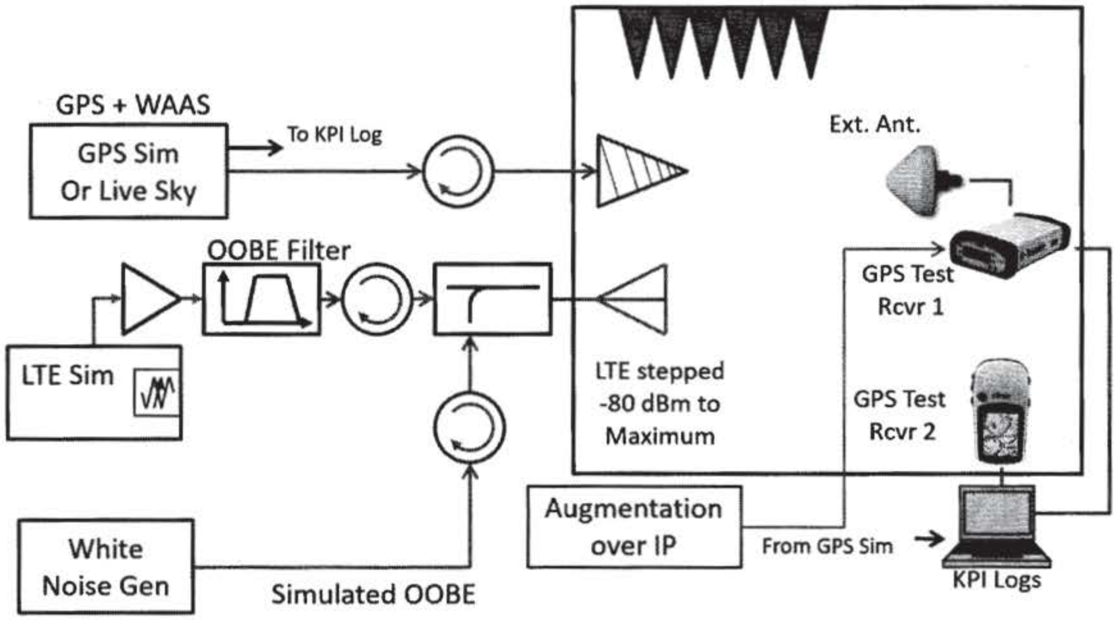

Figure 4 Simplified radiated GPS KPI measurement schematic. MSS augmented High Precision receivers will use live sky GPS+Augmentation signals.

Knowledge of GPS receiver antenna gain patterns (azimuth, elevation, and polarization) will be required if it is necessary to project the received power levels back to emitter antennas in use case analyses. To avoid having to take radiated measurements at multiple incidence angles on the antenna, devices are tested at one angle measured in the laboratory, and, in the use case analyses, adjusted for the angles of arrival called for by specific use cases. The 3D antenna pattern data from the equipment manufacturers will be required for this purpose, absent which, realistic assumptions will be made. Note that the laboratory set up does not try to emulate the actual angles of arrival of the LTE and GPS signals – they are setup with convenient angles of arrival that produce strong responses from the GPS antenna.

Note also that the GPS signals from different satellites are combined and radiated as one composite signal towards the GPS receiver with an angle of arrival corresponding approximately to the antenna's boresight. The LTE signal is likewise radiated with an angle of arrival within +/- 45^0 of boresight. In the use case analyses, the received powers of LTE signals will be adjusted by the difference in an antenna gain between the angle of arrival used in the laboratory and that called for by a specific use case.

2.5.1.1 Motion Testing

General Location and Navigation devices are tested with motion. This means that the GPS simulator uses an NMEA file recorded during a short drive around a loop. During GPS sensitivity testing the latitudes and longitudes from the NMEA file along with the start date and time of the simulation are used to calculate satellite positions and therefore the received GPS signals.

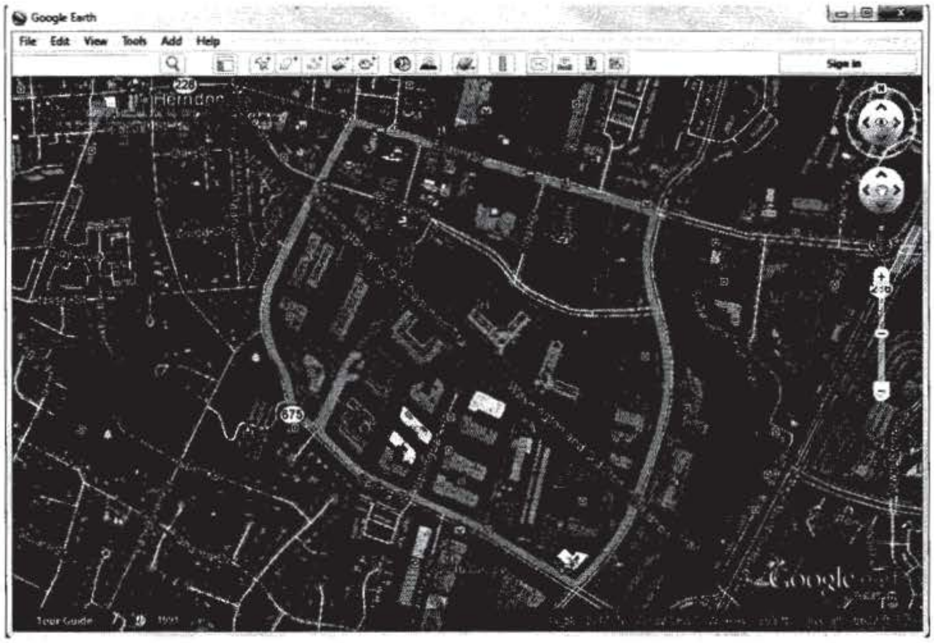

Figure 5 Google Earth view of motion testing drive route. The route was driven in the clockwise direction.

2.5.1.2 Static Testing

Static testing is the condition where the GPS simulator generates GPS signals corresponding to those that a GPS receiver at a fixed location would receive. The GPS device is not moving.

2.5.1.3 Live Sky

Live sky testing is used for some High Precision devices that are augmented with real time correction signals. This is because live sky testing provides a convenient way to apply the corrections signals. An example is the MSS augmented High Precision devices class. A high quality GPS antenna is installed on the roof of the building where the RF anechoic chamber is located. The GPS signal are amplified and connected to the GPS source antenna in the chamber to produce the "Live Sky" signal.

2.6 Dependencies and Assumptions

The post measurement analysis of the data involves comparison of the measured received estimated positions (for position measuring receivers) and time with the true values. The basic process is to compare true position and time with received values measured by the device. The following are recorded as functions of LTE downlink and uplink signal levels at the receiver: 2D and 3D mean position errors as well as the C/N_0 values reported by the GPS receiver at an output reporting period (typically) of 1 or 2 seconds. In the presentation of results, a parameter called the "mean position error" is used as the KPI. This is the *mean value of the magnitude of the error in the position reported by the devices at full output sampling rate*, indicated above. It is not the error in the mean position calculated over 3 minutes. The C/N_0 values presented are averaged over all satellites used by the device and over the 3 minute observation period. Additional analysis is outside the scope of this document will be performed to assess the impact to the user of KPI degradation in real life scenarios.

Analyzing test results with motion testing is based on matching GPS timestamps of the recorded simulator output and the device being tested, and comparing the 2D positions at each timestamp.

2.6.1 LTE Signals and Bands

Only the full 10 MHz bandwidth version of LTE signals are used in the measurements. Downlink LTE signals are assumed to be supporting many devices and have all LTE resource blocks assigned.

Uplink LTE signals are representative of high data rate, with all resources blocks assigned and the device transmitting at the maximum EIRP of 23 dBm. The high data rate case is the extreme worst case since it represents transmitting on the most resource blocks over time. Lower data rates will be experienced in the field as well as lower radiated power, since many of the resource blocks are not being used, and a base station will rarely, if ever, assign 100% of the resources to a single device.

The bands for the LTE signals used in the KPI measurements are shown below. Only 10 MHz bandwidth LTE signals are used.

LTE Direction	LTE Band	LTE Throughput (Simulated)
Downlink	1526-1536 MHz	Max. Throughput
Downlink	1670-1680 MHz	Max. Throughput
Uplink	1627.5-1637.5 MHz	Max. Throughput
Uplink	1646.5-1656.5 MHz	Max. Throughput

2.6.2 LTE Uplink Signal Generation OOBE Noise Floor

The uplink LTE signals simulate the entire output power spectrum, and represent the maximum that can be transmitted from an LTE device. The OOBE EIRP Emission limit for a handheld LTE device is -105 dBW/MHz from 1559 MHz to 1608 MHz, in accordance with the parameters Ligado has requested in its pending FCC license modification applications. The tests emulate the LTE devices emitting OOBE at representative levels.

The LTE uplink has a maximum power of +23 dBm over a 10 MHz bandwidth. The noise floor does not exceed -105 dBW/MHz referenced to the inband level. These are EIRP values.

The schematic shows a wideband white noise generator output combined with the LTE uplink signal to produce a test signal with the power spectral density shown above. The power spectral density (PSD) of the added white noise represents Ligado's current commitment of uplink OOBE, projected from a Ligado device to a GPS receiver at a distance of 1 m and assuming a net antenna coupling loss of 5 dB.

Table 2 shows the conversion from -105dBW/MHz at the transmitter to the OOBE power received at the device under test.

Table 2 Basis of OOBE PSD applied to the GPS device under test

-105 dBW/MHz	Ligado LTE Devices OOBE emission limit	
-165 dBW/Hz	- 60 dB	Convert MHz to Hz
-135 dBm/Hz	+30 dB	Convert dBW to dBm
-171.4 dBm/Hz	-36.4 dB	Path loss at 1 m separation
-176.5 dBm/Hz	-5 dB	Antenna Coupling
-176.5 dBm/Hz	Power received at the GPS Device Under Test	

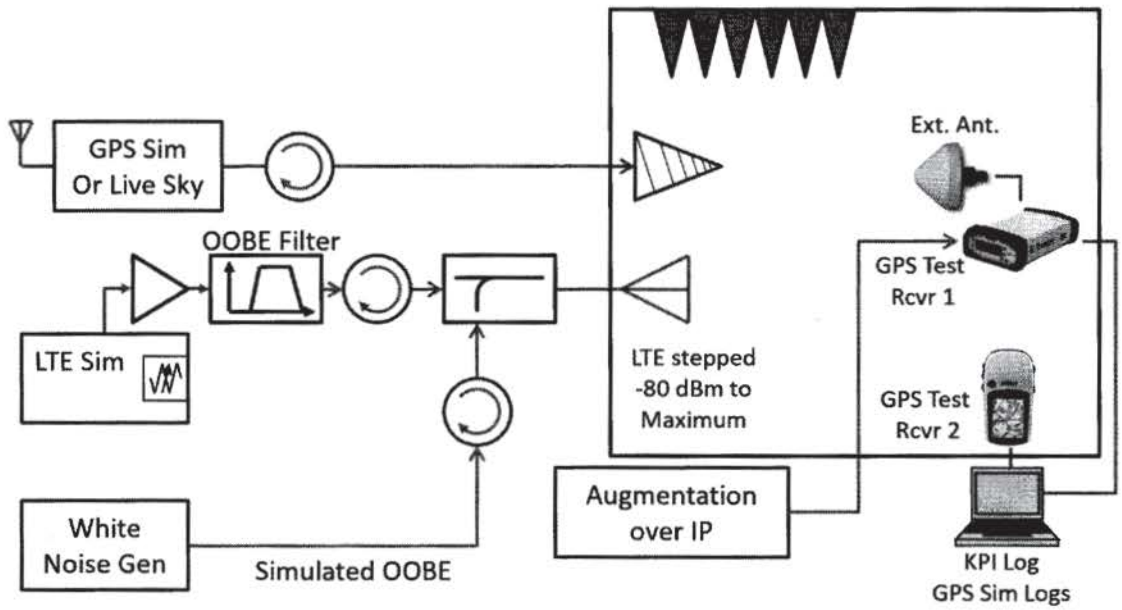

Figure 6 Schematic for producing LTE uplink OOBE noise -176.5 dBm/Hz at the GPS receiver

2.6.3 GPS Condition

The GPS signal conditions shown below are simulated during static and/or motion testing depending on the device type.

Condition	Number	GPS Level	WAAS Levels
Open Sky	8+ satellites	-130 dBm	-128.5 dBm
Impaired GPS Signal	8+ Satellites	-142 dBm	-142 dBm

The combinations of GPS signal condition and device dynamics used in testing are summarized in the table below.

GPS Signal Condition	GPS Device Condition
Open Sky	Static Simulator
Impaired GPS Signal	Static Simulator
Open Sky	Motion Simulator
Impaired GPS Signal	Motion Simulator
Live Sky	Live Sky (antenna mounted on roof of testing lab)

2.6.4 Other GPS Impairments

No GPS ionospheric impairments are added to the simulations.

2.7 Equipment List

The list below includes the equipment required for measuring the sensitivity of GPS KPIs to LTE signal levels

1. Spirent GPS Test Set capable of introducing WAAS signals, and capable of playing back recorded NMEA motion files
2. MSS Augmentation signal sources
3. RTK Augmentation message generation and RF, WiFi, or Ethernet RTK signal source
4. LTE Signal Generator
5. RF Amplifiers
6. RF Attenuators
7. RF Signal Combiners, isolators, couplers
8. LTE TX OOBE Filters
9. LTE TX and GPS TX Antennas
10. GPS RX Antennas
11. GPS RX Filters

2.8 Calibration and Pretest

Prior to collecting detailed KPI data the devices are characterized for their basic performance levels to ensure the devices are operating properly. It is also vital to understand the intrinsic random variations in KPIs that the GPS system produces under "no-interference" conditions. This involves applying a GPS constellation signal at a fixed, known level to each device and recording the KPI's for each device. No adjacent band signals are present during these measurements.

Prior to data collection it is important to verify that the thermal noise floor has not been increased and that there are no spurious intermodulation signal produced by interactions between the GPS and LTE signal generators.

3 KPI MEASUREMENT PROCEDURE

3.1 Measurement Sequence

The basic sequence to measure the changes in KPIs as a function of LTE signal level is shown below. The approach is to apply the LTE signal and increase the level in small steps while capturing statistically valid KPI data sets at each step. A baseline set of KPI data without the LTE signal is also collected during the GPS-only phase. The duration of the GPS-only phase is 2 hours. The reason is to capture both the short-term random position variations as well as the long-term position variations caused by changes in the satellite constellation which modify the composition of satellites used to calculate position.

The GPS simulator, in addition to standard L1 C/A-code GPS signals, provides WAAS augmentation signals when the test receiver is WAAS capable. In the case of non-MSS-augmented High Precision receivers, the augmentation signal was provided by an IP network connection; In the case of MSS augmented High Precision receivers, the augmentation and GPS signals is received by a wideband antenna, amplified and re-radiated in the RF chamber if feasible. Receivers using augmentation signals may be able to remove a large part of these errors but non-augmented receives (including High Precision receivers operated in Autonomous mode) experience a baseline rms error, as they do in real life operation, that will be present in the absence of LTE signals. The KPI statistics show the impact of the LTE signals on the baseline error.

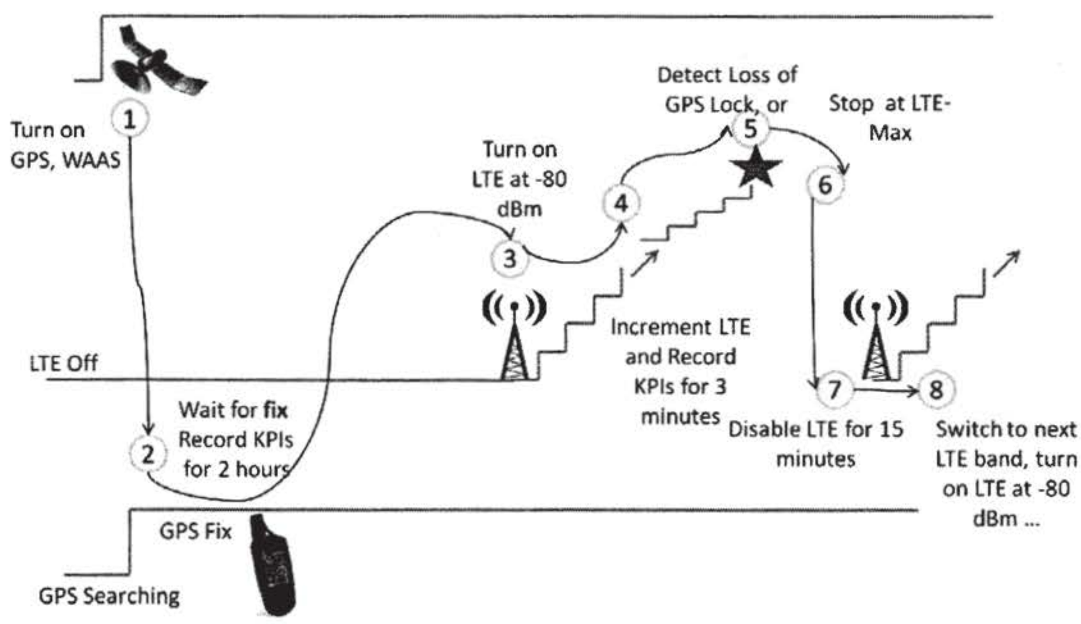

Figure 7 Generic GPS KPI measurement sequence

The pseudo-code description for the MEASURE_KPI_SET() sequence is given below. The parameter TRECORD must be long enough to capture a large enough set of KPI measurements so that statistically valid KPI averages and standard deviations can be calculated. TRECORD may be as long as one minute or more for devices reporting KPI values at a low rate.

```
Power GPS device
  Apply GPS signal
  Wait for the GPS receiver to enter the fix-found state
  Record baseline GPS NMEA signal parameters, and KPI values for
        2 Hours.
  Apply LTE signal, and OOBE signal if in an uplink band, at a
signal level of -80 dBm.
  Loop from -80 dBm until LTE level reaches -10 dBm.
    record GPS NMEA signal parameters and KPI values for 3
        minutes.
    increase LTE level by (coarse 5 dB steps up to -40 dBm and
then fine 2 dB steps)
  Remove LTE Signal
```

3.2 High Precision Measurements

3.2.1 Situation: High Precision Location

High Precision GPS receivers may have wider RF front end bandwidths than other GPS devices. This may be motivated by a need to receive an MSS augmentation signal in the adjacent 1525-1559 MHz MSS band and to share the RF front end circuitry between the MSS augmentation signal receiver and the GPS receiver. Others use augmentation signals in the UHF and other bands and do not need to have such wide passbands.

3.2.2 Goals

First, to characterize the performance of the High Precision receivers and antennas in the target list. Second, for receivers where the antenna and receiver are not integrated into one unit, determine if the use of known high immunity antennas can improve adjacent band compatibility. Test and compare the performance of high precision receivers which use antennas which limit the receive bandwidth to the GNSS band.

3.2.3 Plan

Measure representative high precision GPS receivers, capture and store KPI data as a function of LTE signal strength. Repeat the measurement with a high interference immunity antenna.

3.2.4 Analysis:

Compare true position with received values. Plot RMS 3D location errors, satellite count, and C/N_0 vs. LTE signal levels for each test frequency, with and without high immunity antennas present. Record the availability of augmentation signal vs. signal level.

3.2.5 Assumptions

MSS augmentation signals and RTK augmentation signals are generated and supplied to the GPS device under test. Access is available to 3D location error data.

3.2.6 Measurement Test Sequence

Pseudo-code for measurement of high performance GPS receivers is given below for static testing

```
For each GPS condition (Open Static, Live Sky)
  For each downlink frequency band (1531, 1675)

    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1651)
    MEASURE_KPI_SET()

Enable Augmentation Signals
Setup test for Live Sky GPS condition
  For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
  For each uplink frequency band (1631, 1651)
```

```
MEASURE_KPI_SET()
```

3.2.7 MSS Augmentation Signal

As proprietary augmentation signal simulators were not available, chamber testing with simulated signals (augmentation and GPS), as performed for most other devices, was not possible. Therefore, live sky signals, containing actual augmentation and GPS signals, were used.

The schematic in Figure 8 below shows how an external antenna can be used to gather GPS and MSS augmentation signals and apply them to a GPS receiver under test in an anechoic chamber. Without a location reference from a GPS signal generator, the "true" location is estimated from a long term average under LTE signal "Off" conditions.

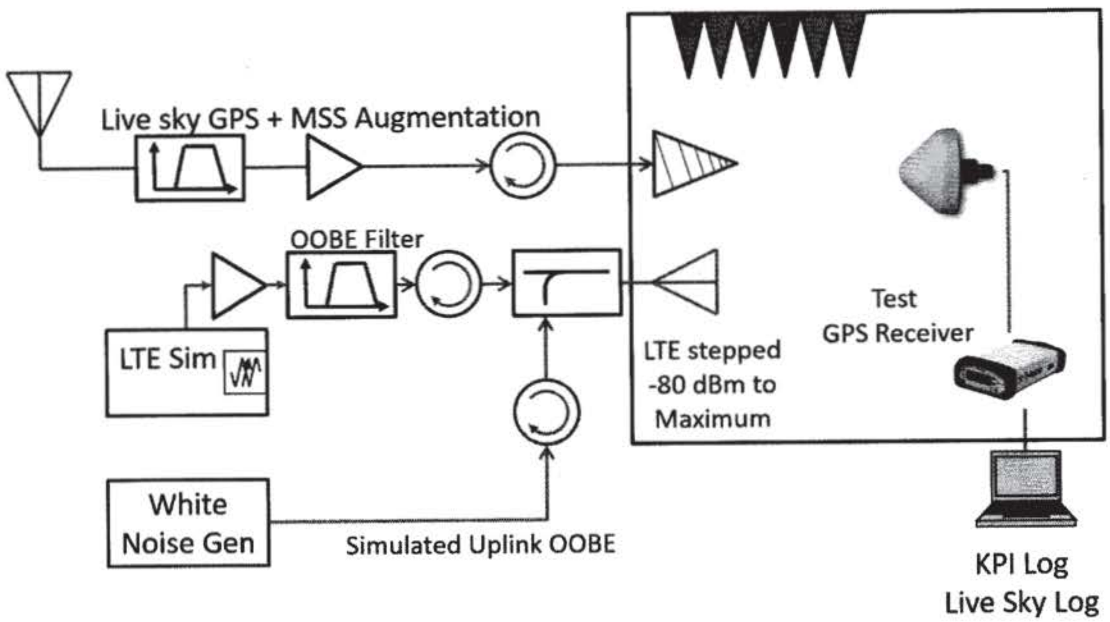

Figure 8 External GPS plus MSS augmentation signal capture

3.2.8 RTK Augmentation Signal

Commercial and public RTK correction data is available from many sources. The schematic below shows a system for using commercial internet (IP network) based RTK.

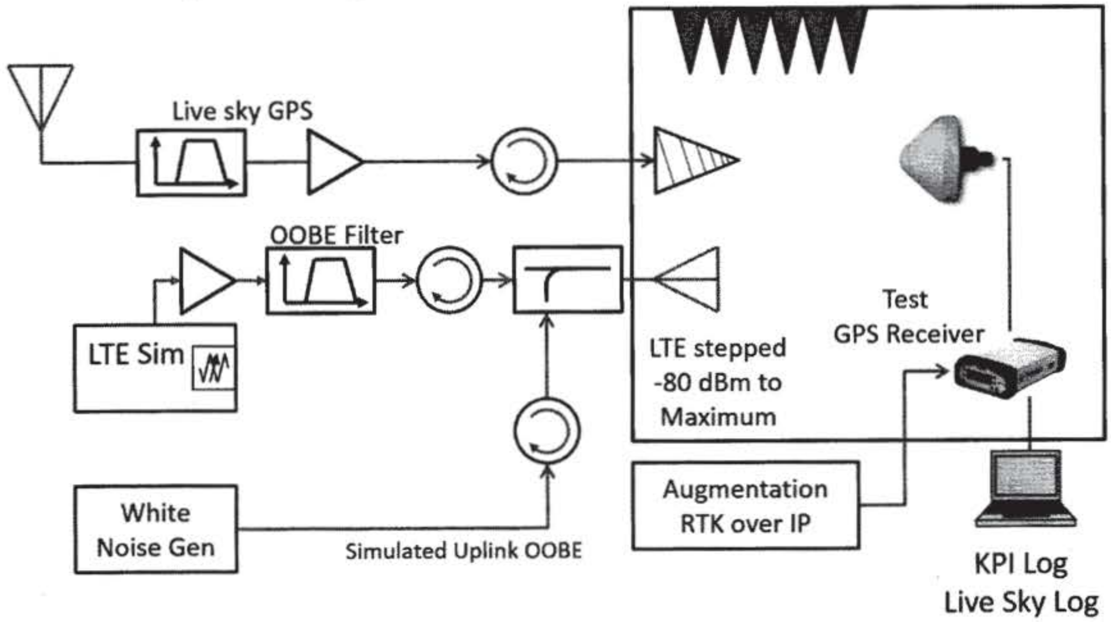

Figure 9 Insertion of commercial RTK into test chamber

3.3 Cellular Device Measurements

3.3.1 Cellular Device Situation

Cellular devices and smart phones have rapid replacement cycles. Smart-phones are very commonly used for mapping, location, and navigation relying on embedded GPS receivers as well as network provided location information. Bestselling devices in the latter half of 2015, the time of these measurements, were not available or marketed in 2011. GLONASS capability is now included in high volume GPS chipsets and this capability may have resulted in different RF front end filter characteristics for the embedded GNSS receiver in Cellular devices.

3.3.2 Desired Goals

Characterize the performance of the latest, high sales volume cellular devices to update the performance baseline.

3.3.3 Plan

Measure only the high sales volume devices and use 3GPP Sensitivity, Accuracy, and Dynamic Range testing in a radiated environment to capture 3GPP specific KPIs for selected LTE levels. Capture and store location KPI data as function of LTE signal strength for devices not testable using 3GPP procedures.

Analysis: Use TWG defined, 3GPP-adapted test plans, which are based on measuring statistics of 2D position error.

Figure 10 below shows the use of a cellular base station simulator to capture 3GPP A-GPS KPIs.

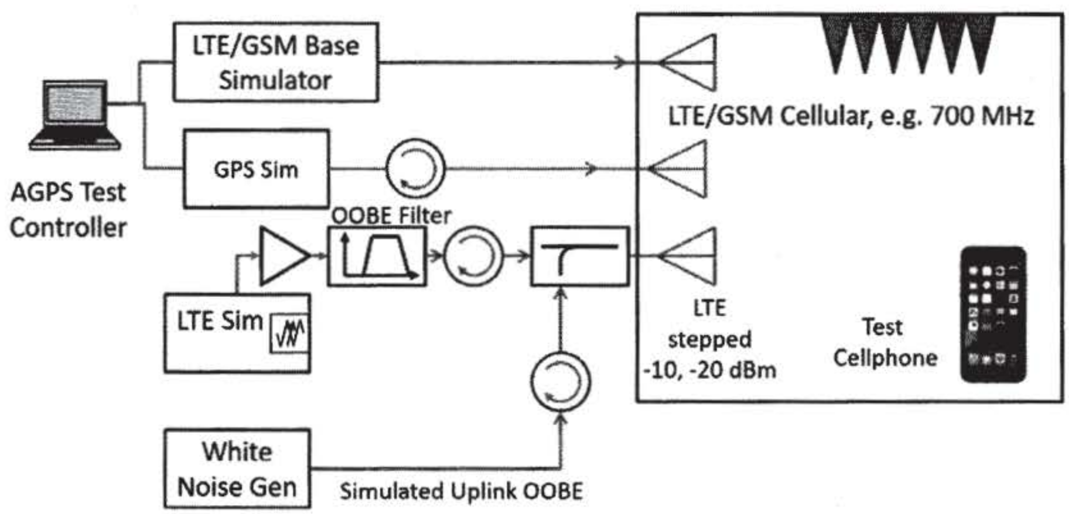

Figure 10 Cell phone KPI measurement with 3GPP base station simulator

3.3.4 Assumptions

Reception of signals from other GNSS constellations is not tested.

Access to KPIs or NMEA sequences is available and exportable to an external logging system.

3.3.5 A-GPS KPI Measurement Sequence

The three A-GPS tests listed in Section 2.1 are implemented as functions in an A-GPS test controller. This controller controls the output of the GPS simulator while querying the cellular device for information about its current state and position.

3.3.6 Position Error KPI Measurement Sequence

A pseudo-code description of the cellular device measurement sequence is listed below for position error KPI measurements.

```
For each GPS condition (Motion Open)
  For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
  For each uplink frequency band (1632, 1651)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

3.4 General Location and Navigation (GLN) Device Measurements

3.4.1 General Navigation Situation

The present tests will limit the maximum received LTE power to -10 dBm.

3.4.2 Desired Goals

Characterize the KPI performance of the latest, high sales volume GLN GPS devices.

3.4.3 Plan

Measure high sales volume devices and capture and store detailed KPI data as function of LTE signal strength.

3.4.4 Assumptions

Access to KPIs or NMEA sequences is available and exportable to an external logging system.

3.4.5 Measurement Sequence

A pseudo-code description of the cellular device measurement sequence is listed below.

```
For each GPS condition (Motion Open, Motion Impaired)
  For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
  For each uplink frequency band (1631, 1651)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

3.5 Aviation (uncertified) Measurements

3.5.1 Aviation (uncertified) situation

Uncertified aviation devices offer a wealth of information to pilots. GPS receiver data is linked to maps, terrain databases, and airport databases. Cellular devices are very widely used and it is likely they will operate in close proximity to aviation devices while a plane is on the ground. Uplink signal levels corresponding to those that might be seen for distances as close as a few meters need to be tested.

Airplanes are also able to view multiple base-stations when in the air at cruising altitudes. Testing with downlink signals is an important consideration at lower altitudes during takeoff and landing.

3.5.2 Plan

Measure high sales volume devices and capture and store detailed KPI data as function of LTE signal strength.

3.5.3 Assumptions

Access is available to 2D location error data and NMEA data.

3.5.4 Test Sequence

The pseudo-code for static measurements is given below

```
Set GPS condition to Motion OPEN
For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

4 Analysis

At each LTE power level many KPI data samples are collected. The mean value of each KPI, over a 3-minute observation period, is calculated for each power level sample set and logged in one of the KPI Test Data Tables.

Raw NMEA and other data from GPS devices are stored in the format it is received in. It is likely that the formats will be different for each device.

Relative changes in the mean KPI error are the measure of interference used in later work.

Position error KPIs use different reference locations (true positions) depending on the device type. The reference location types are shown below. Certain devices require a search procedure to find the best fit since timestamps provided in synthetic NMEA data reflect device clock time and not GPS system time. This analysis calls for extending the measurement interval.

GPS Condition	Location Reference
Static	Static Simulator Reference
Motion	GPS Simulator Output Log
Live Sky	R9 Average
A-GPS	GPS Simulator Internal

4.1 Statistical Analysis

In order to translate the KPI vs. LTE signal level statistics collected in the measurements to a probability of GPS functionality impairment, analysis beyond device measurements is needed to determine the likelihood, frequency, and expected duration that a user will experience LTE levels that cause an increase in KPI standard deviation. Data is available from previous adjacent band compatibility testing, as well as from existing LTE networks that can be used to develop a statistical model for LTE signal levels experienced by GPS receivers under different LTE deployment plans. Comparison of these statistics and scenarios with the KPI sensitivities to LTE signal strength will produce an assessment of how often and how much the presence of the LTE network will impact user functionality.

5 Change History

Version	Date	Description
V0.6	June 25, 2015	Preliminary Draft
V0.8	July 22, 2015	Added detail regarding 3GPP specific tests for cell phones Updated Device List Updated KPI Table Updated GPS Impairments table Added detail for pretest scenario: added un-impaired GPS pretest

V1.0	July 27,2015	Version 1.0
V1.1	August 24, 2015	Updates to warm start TTFF section in response to NPSTC. Updates to certified aviation section
V1.2	Sept. 28, 2015	Add WAAS testing added note to test at higher LTE power in response to NPSTC. Added re-acquisition test in response to NPSTC. Updated testing diagrams. Updated OOBE description
V1.5	February 5, 2016	Updated to reflect final test procedures Updated device list. Certain devices could not be made to export KPI data. Aviation devices were removed. Single ramp-up LTE signal level and GPS only intervals detailed. Added detail regarding re-acquisition testing.
V2	May 9, 2016	Update to Device List Added details of Impaired Test